REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

Public Reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimates or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188,) Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE _January 10, 2001_	3. REPORT TYPE AND DATES COVERED _Final Report; 01 Sep 96 - 31 Aug 00_

4. TITLE AND SUBTITLE _Integrated measurement System for Rapid Shape Measurement, Model Verification and NDE_	5. FUNDING NUMBERS _DAAH04-96-1-0420_

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) _University of South Carolina Dept. of Mechanical Engineering Columbia, SC 29208-0000_	8. PERFORMING ORGANIZATION REPORT NUMBER _3_

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSORING / MONITORING AGENCY REPORT NUMBER _ARO 36361.1-RT-DPS_

RECEIVED JAN 23 200[1]

11. SUPPLEMENTARY NOTES
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13. ABSTRACT (Maximum 200 words)

Extensive studies of shape measurement systems have been completed. Both numerical simulations and controlled experiments have been performed. Results have shown that, for fringe patterns having sensor plane fringe spacing from 3 to 30 pixels, the resulting phase error can be reduced to less than 0.02 radians by controlling the spatial frequency of the signal and noise, as well as the contrast in the pattern.

Studies of data integration methodologies have also been completed. Results demonstrate that the procedure developed by the authors is both robust and accurate when registering and integrating multiple, overlapped data sets. The effects of key variables in the registration process have been quantified through numerical simulations. Results indicate that when the feature size divided by the overlapped region size, $\alpha = fs/ls \leq 0.5$, and the mesh size divided by the feature size, $\beta = ms/fs \leq 0.25$, the algorithm can accurately and efficiently register and integrate multiple data sets with a relative error, $\varepsilon = ra/ms \leq 10\%$.

Finally, studies of automated registration processes have been performed. Local differential geometry properties such as gaussian curvature, K, and mean curvature, H, along with their signs have been used to successfully automate the process of integration of separate shape measurement data sets.

14. SUBJECT TERMS Data integration; Surface feature recognition; Automated data patching Shape measurement; Parameter assessment; Experimental verification	15. NUMBER OF PAGES _9_
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

Enclosure 1

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REPORT TITLE: *Final Report for "Integrated Shape Measurement System for Rapid Shape Measurement, Model Verification and NDE.*

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Sincerely,

Michael A. Sutton

Michael A. Sutton

1.   Statement of the Problem Studied and Significance

This research was directed towards the development and experimental verification of a stereo-vision measurement methodology which will be used to (a) accurately determine the three-dimensional shape of a complex component either in the initial or deformed states, (b) convert the measured surface displacement data into a functional form using surface fitting methods such as wavelet transformations and (c) perform these operations rapidly.

The significance of this work is in two areas. Firstly, the measurement of surface shape and rapid conversion of the measurements into an accurate functional relationship is a major step in improving existing computer-aided engineering applications for more rapid design and manufacture of components. Secondly, the experimental data base for the deformation of complex structural components is essential to the verification of solid model equation solvers (e.g., finite difference, finite element, boundary element) for large structures. This is particularly important since government organizations such as NASA have proposed a GLOBAL--LOCAL analysis methodology[1] to ensure that local variations (e.g., small cracks, rivets, frame reinforcing members) can be properly accounted for in the model

2.   Summary of Most Important Results

Measurement Methodology

An accurate camera calibration procedure and improved phase extraction procedures using a modified Hilbert Transform [1,2] with Laplacian Pyramid and Flood-Fill algorithms have been developed and successfully demonstrated for measurement of the full (X, Y, Z) positions of surface points using single frequency, fringe projection profiling methods [3]. Detailed numerical simulations and controlled baseline experiments have been performed to quantify the key error sources in the measurement process and verify the accuracy of the approach.

Simulation results indicate that, for fringe patterns having sensor plane fringe spacing from 3 to 30 pixels, the resulting phase error can be reduced to less than 0.02 radians provided that

(a) the spatial frequency of the background noise sources meets the inequality

$k = 2\pi/\lambda < 0.01,$

(b) the multiplicative noise terms have spatial frequency content at least three times smaller than the fringe pattern,

(c) the multiplicative noise factors have an amplitude at least ten times smaller than the fringe pattern

(d) the recorded fringe patterns have an amplitude of at least 64 gray levels and

the recorded fringe patterns have a random noise to signal amplitude ratio < 0.010.

Baseline experiments have been performed which demonstrate that the error sources (e.g., random intensity fluctuations, contrast reduction) quantified in the numerical simulations are in good agreement with physical measurements. Specifically, results indicate random spatial changes in the intensity pattern due to variations in

object surface reflectivity introduce negligible bias and a random variation of 0.05 radians in the extracted phase for almost all experiments performed.

To demonstrate the method for applications, spatial (X, Y, Z) data has been obtained by both coordinate measurement machine (CMM) and fringe projection for both a planar surface and a turbine blade. Results indicate that (a) the CMM measurements are in good agreement with fringe projection data for both cases and (b) simulation estimates for the fringe projection errors are consistent with measurements.

Taken together, the experimental studies and numerical simulations confirm that very high accuracy shape measurements can be made with single frequency projected grids. Specifically, phase errors of less than 0.04 radians on a pixel-by-pixel basis are achievable for a wide range of fringe density using the proposed method. Furthermore, the experimental and numerical results demonstrate conclusively that it is possible to design both a fringe projection system and a measurement process to achieve a pre-specified accuracy and resolution in the point-to-point measurement of the spatial (X, Y, Z) positions.

Data Synthesis

Efficient, accurate integration of multiple sets of surface profile data without requiring accurate relative positional information is an important step in the reverse engineering process. Results from the current work [4] demonstrate that the procedure developed by the authors is both robust and accurate when registering and integrating multiple, overlapped data sets. The effects of key variables in the registration process have been quantified through numerical simulations. Results indicate that when

the feature size divided by the overlapped region size, $\alpha = fs/ls \leq 0.5$, and the mesh size divided by the feature size, $\beta = ms/fs \leq 0.25$, the algorithm can accurately and efficiently register and integrate multiple data sets with a relative error, $\varepsilon = ra/ms \leq 10\%$.

It is important to note that we have selected curvature as the dominant surface feature for this work. Currently we are performing additional tests to determine which surface features are best for registration and integration of multiple overlapped data sets.

Automatic Registration

A study of the viability of various mathematical representations for surface features for automating the registration process is presented [5]. Local differential geometry properties such as gaussian curvature, K, and mean curvature, H, along with their signs are used to categorize local surface shapes into one of eight invariant basic quadric types [6]. Each data cloud is processed to eliminate outlier points and triangulized to obtain a polygonal mesh. After smoothing of the polygon meshes, features were extracted by region growth segmentation based on surface types. Results from our studies indicate that (a) measurement noise deforms the shape and number of features found on the surface as a result of the segmentation, making it unlikely that *identical* feature patterns can be located in the overlapping region, (b) provided that the shape measurement accuracy is consistently maintained at a threshold value, similar features can be identified in the overlapped regions of neighboring point clouds and (c) for a wide range of typical applications, automation of the registration process is shown to be feasible using local features.

3.   Listing of Publications

Book Chapters

1.   ***Photomechanics***, Chapter 10 on "Advances in 2D and 3D Computer Vision for Shape and Deformation Measurements", Topics in Applied Physics, 77, 323-372 (2000) Edited by Pramod Rastogi.

2.   ***Trends in Optical Non-Destructive Testing and Inspection***, Chapter 38 on "Computer vision applied to shape and deformation measurement", El Sevier, 571-591 (2000) Edited by D. Inaudi and Pramod Rastogi.(2000

Papers accepted or published in peer-reviewed journals

1.   W. Zhao, M.A. Sutton, S.R. McNeill, H. Schreier and Y.J. Chao, "Accurate Surface Shape Measurements: Development and Assessment of a Fringe Projection Methodology", accepted for publication in *Intl Journal of* **Experimental Mechanics**

2.   Ning Li, Peng Cheng, Michael A. Sutton, Stephen R. McNeill and Yuh J. Chao, "Accurate Reconstruction of Surface Profile Data Sets", to be published in *Intl Journal of* **Experimental Mechanics (2001).**

Papers published in non-peer-reviewed journals or conference proceedings

1.   M.A. Sutton,   S.R. McNeill, J.D. Helm and H. Schreier, Proceedings of the International Conference on Advanced Technology in Experimental Mechanics in Ube, Yamaguchi, Japan, July 21-24, 1999, "Full-field, Non-contacting Measurement of Surface Deformations on Planar or Curved Surfaces Using Advanced Vision Systems", Volume 1, 145-151 (1999).

2.   W. Zhao, H.W. Schreier, S.R. McNeill, M.A. Sutton and Y.J. Chao, "Fringe Projection for Accurate, Quantitative Measurement of 3D Object Shapes", SEM Conference on Experimental Mechanics, 452-454 (1998).

3.   P. Cheng, N. Li, M. A. Sutton, S.R. McNeill, "Registration of Surface Profile Data Sets with Relaxation Labeling Process", Proceedings of SEM International Conference , (2000).

4.   Peng Cheng, Ning Li, Michael A. Sutton, Stephen R. McNeill and Yuh J. Chao, "Integrating Multiple Patches of Surface Profile Data", Proc. of Soc. For Experimental Mechanics Conference, 161-164 (1999).

5.   Peng Cheng, Ning Li, Michael A. Sutton, Stephen R. McNeill and Yuh J. Chao, **"An Automatic Method For Registering Geo-spatial Terrain Data",** Proc. of American Soc. Of Remote Sensing and Photogrammetry Conference in Tampa, Florida (1998)

Papers presented at meetings, but not published in conference proceedings

NONE

Manuscripts in review
1.   Peng Cheng, Ning Li, Michael A. Sutton, Stephen R. McNeill and Yuh J. Chao, "Automated Point Cloud Registration with Invariant Surface Feature", in review with *Intl Journal of* **Experimental Mechanics**

Technical reports to ARO
1.   First Progress Report for Grant # DAAH04-96-1-0420, *"Integrated Measurement System for Rapid Shape Measurement, Model Verification and NDE",May 12, 1997.*

2.   Second Progress Report for Grant # DAAH04-96-1-0420, *"Integrated Measurement System for Rapid Shape Measurement, Model Verification and NDE", April 8, 1999.*

3.   Final Progress Report for Grant # DAAH04-96-1-0420, *"Integrated Measurement System for Rapid Shape Measurement, Model Verification and NDE", January 11, 2001.*

4.   **Listing of Graduate Students with Degrees**

Name	Degree	Date of Degree
Mr. Peng Cheng	Ph.D. in Mech. Engr	Summer, 2001
Mr. Wenzhong Zhao	Ph.D. in Mech. Engr.	Fall, 2001
Mr. Jeffrey D. Helm	Ph.D. in Mech. Engr.	Summer, 1999
Mr. Hubert Schreier	Ph.D. in Mech. Engr.	Summer, 2001

5.   **Report of Inventions**

NONE

6.   **Bibliography**

[1]   Zweig, D.A., Hufnagel, R. E., "A Hilbert Transform Algorithm for Fringe-Pattern Analysis," SPIE Vol. 1333, Advanced Optical Manufacturing and Testing, 1990.

[2]   Jaehne, B., Practical Handbook on Image Processing for Scientific Applications, CRC Press, 1997

[3]   W. Zhao, M.A. Sutton, S.R. McNeill, H. Schreier and Y.J. Chao, "Accurate Surface Shape Measurements: Development and Assessment of a Fringe Projection Methodology", accepted for publication in *Intl Journal of* **Experimental Mechanics.**

[4]   Ning Li, Peng Cheng, Michael A. Sutton, Stephen R. McNeill and Yuh J. Chao, "Accurate Reconstruction of Surface Profile Data Sets", to be published in *Intl Journal of* **Experimental Mechanics (2001).**

[5]   Peng Cheng, Ning Li, Michael A. Sutton, Stephen R. McNeill and Yuh J. Chao, "Automated Point Cloud Registration with Invariant Surface Feature", in review with *Intl Journal of* **Experimental Mechanics**

[6]   P. J. Besl, R. C. Jain, Invariant Surface Characteristics for 3D Object Recognition in Range Images, Computer Vision, Graphics, and Image Processing, 33, 33-80, 1986